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4.8 A CONCEPT OF MONITORING THE TELESCOPE REFERENCE POINT BY USING MULTIPLE GROUND TARGETS

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ABSTRACT

A new technique for calibrating the telescope reference point and system delay in the KSP-SLR system is proposed. The concept is to estimate the position of the telescope reference point and the system delay simultaneously, using ranging data from five ground targets (three pillars and two benchmarks). The telescope reference point is difficult to identify precisely and may not be so stable over a long time compared with a stability of external ground targets. Therefore, it is necessary to monitor the displacement of the telescope reference point frequently. The technique, called multitarget calibration, enables us to monitor over a long period the changes in the position of the telescope reference point, and to precisely calibrate the satellite laser ranging data using the estimated system delay as well.

Keywords: Satellite laser ranging, Calibration, Telescope reference point, System delay, Ground target,

1. Introduction

The official range value from the satellite laser ranging (SLR) is defined as the time of round trip between the satellite and the station reference point. It is different from a raw range value which includes the system delay, that is, the time required for optical and electric impulse waves to pass through observation devices (laser transmitter and receiver) at a station reference point. Therefore, the system delay must be subtracted from the raw range value for each station. The following are some methods for measuring system delay.

1) External calibration (pre- and postcalibration)

A raw range value is measured before and after the satellite ranging for a ground target, which has a corner cube reflector on top of it. The system delay is calculated by deducting the time for round trip between the ground target and the reference point of telescope from the average of those two range values. The ground survey gives the data of each ground target and the telescope reference point in advance. This method is the conventional method widely used today.

2) Internal calibration (real-time calibration)[1]

Ranging to a corner cube reflector which is, in this case, set around the telescope reference point is done at the same time as satellite ranging. System delay can also be measured by this ranging while the satellite ranging is taking place, in real-time. This method has already been used in some observation stations and has been adopted in the KSP-SLR system[2] as well.

In both of the above methods, the point of intersection which telescope drives (the telescope reference point) is not supposed to change. However, it is difficult to identify the telescope reference point precisely. The ground survey is carried out every year for the telescope reference point and ground targets as well as for the short pillars at each site. The position of telescope reference point is not as stable over a long time as the position of the ground target. The new calibration method we propose in this paper is a way of frequently monitoring the change in the position of the telescope reference point.

This new calibration technique, called multitarget calibration uses ranging to more than four ground targets to find the three-coordinate position of a telescope reference point and the system delay. The telescope reference point and the system delay are estimated with these range values by using the least squares method.

2. The Ground Target

Five ground targets (three pillars and two benchmarks) were installed in each site of the KSP-SLR system. Fig. 1 shows the configuration figure of the ground targets and Fig. 2 shows photographs of the pillars and benchmarks. Fig. 3 shows the structure of a pillar.

The pillars (SLR-L1, SLR-L2, and SLR-L3) have a height of 2.5 m to 10 m and are made of invar. A corner cube reflector for the ranging is installed at the top. Invar is a kind of nickel-iron alloy, that has a linear expansion coefficient at ordinary temperatures of almost 10^{-6} (about 1/10 of normal iron). The base pile of the pillar same as the telescope tower, was installed to the bedrock, and covered with pipe made of stainless steel for distortion-by-sunlight proof. It was designed so that

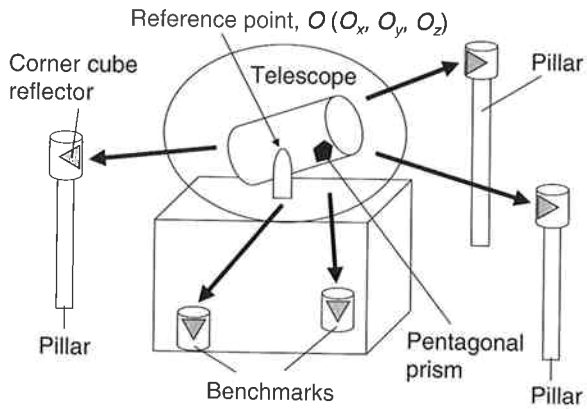
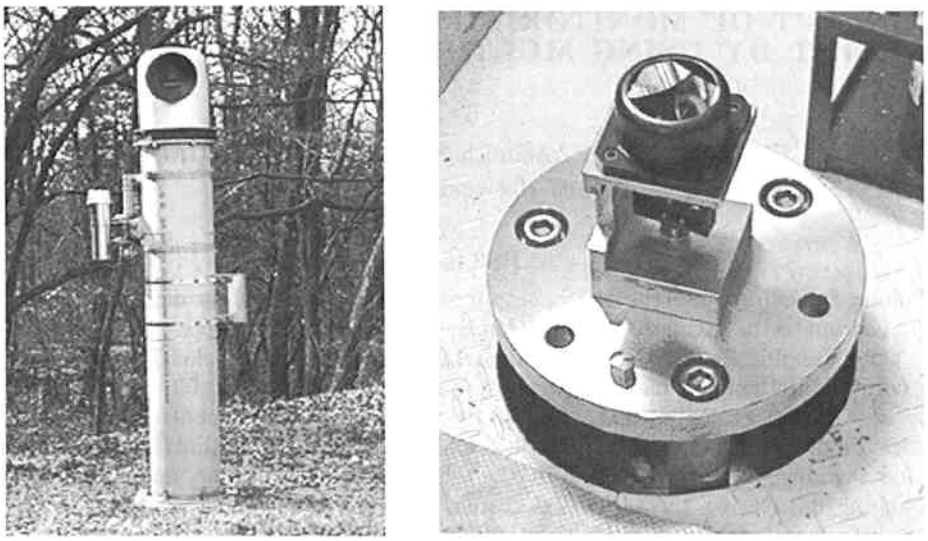


Fig. 1 The configuration of the ground targets in the KSP-SLR system.



(a) Pillar. (b) Benchmark.

Fig. 2 The form of the ground targets.

changes in the position of the corner cube reflector due to surrounding environmental changes might be restrained to less than 1 mm in the horizontal and the vertical components.

The benchmarks (SLR-H1 and SLR-H2) with a height 0.615 m were installed under the telescope inside the telescope tower to estimate the vertical component of the telescope reference point. The ranging to the benchmarks was done with the pentagonal prism because of the limit of the elevation angle of the telescope[2].

In addition to the ground targets, there are three short pillars (SLR-S1, SLR-S2, and SLR-S3), 1 m in height, only used for ground survey. These are stable enough and have the same structure as the ground targets. The short pillars made a rapid survey possible because total stations (light wave range finders) could be installed directly on the top of them without using tripod.

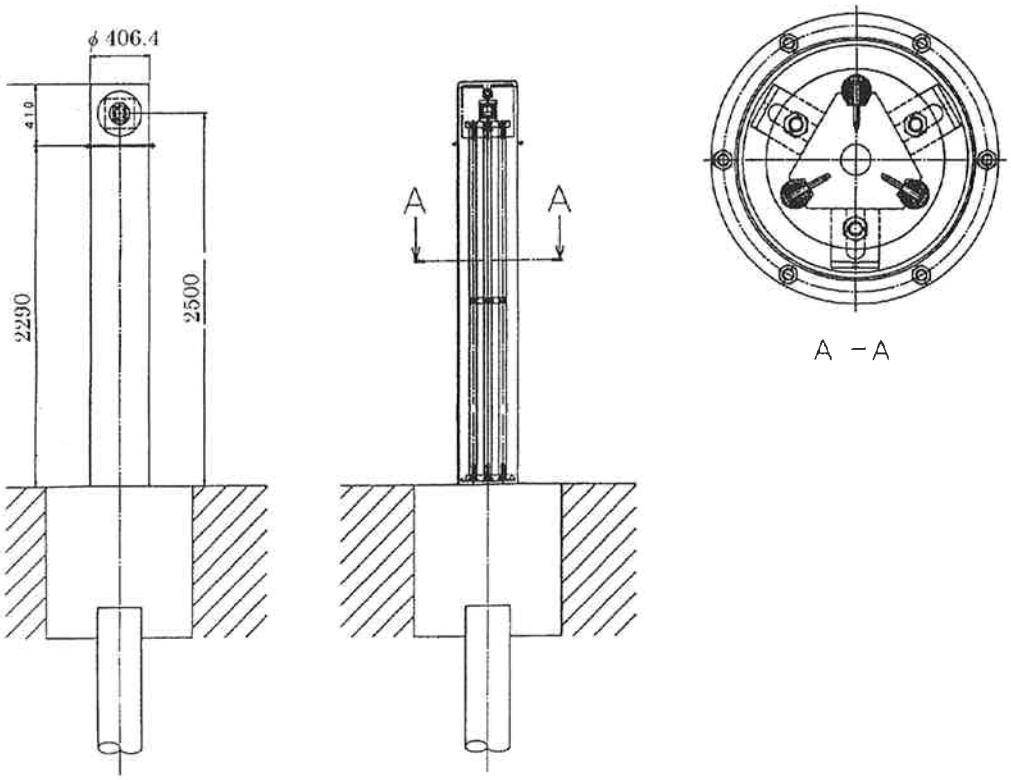


Fig. 3 The structure of the pillar.

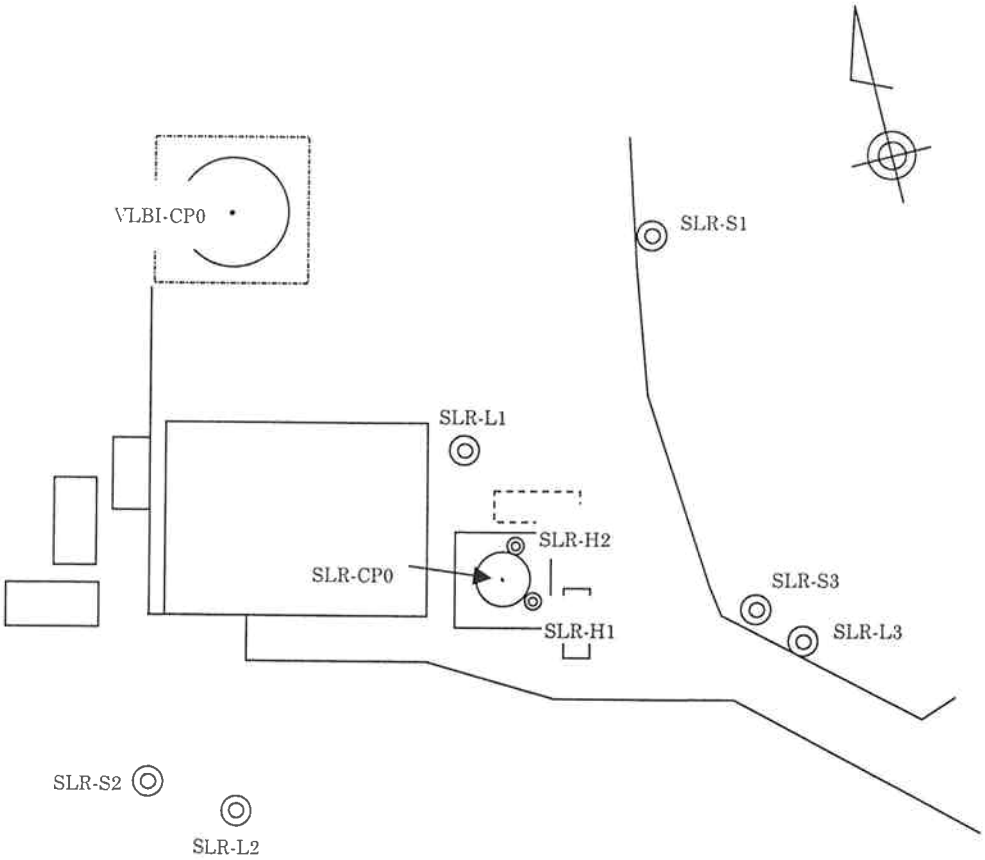


Fig. 4 The configuration of the pillars (SLR-L1, SLR-L2, and SLR-L3), benchmarks (SLR-H1 and SLR-H2), and short pillars for ground survey (SLR-S1, SLR-S2, and SLR-S3) at the Koganei site. SLR-CP0 denotes the telescope reference point of the KSP-SLR. VLBI-CP0 denotes the origin of the antenna of the KSP-VLBI.

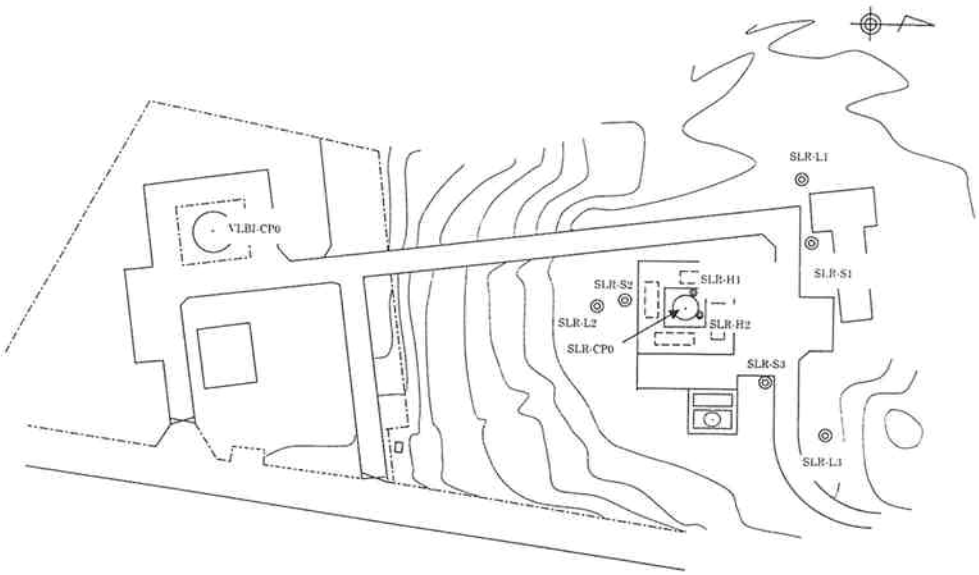


Fig. 5 The configuration of the pillars (SLR-L1, SLR-L2, and SLR-L3), benchmarks (SLR-H1 and SLR-H2), and short pillars for ground survey (SLR-S1, SLR-S2, and SLR-S3) at the Kashima site. SLR-CP0 denotes the telescope reference point of the KSP-SLR. VLBI-CP0 denotes the origin of the antenna of the KSP-VLBI.

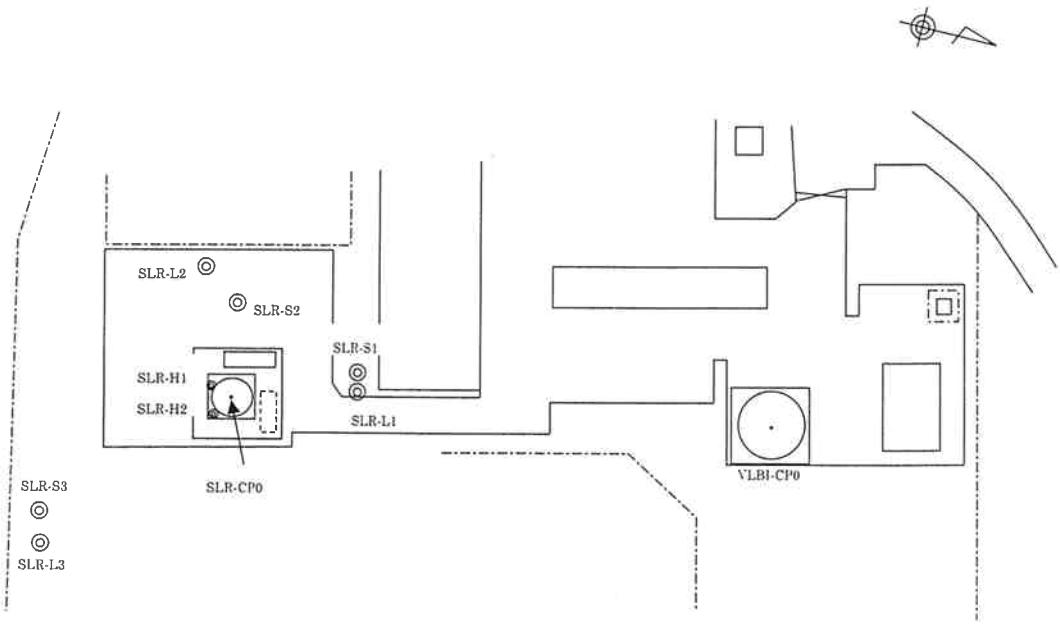


Fig. 6 The configuration of the pillars (SLR-L1, SLR-L2, and SLR-L3), benchmarks (SLR-H1 and SLR-H2), and short pillars for ground survey (SLR-S1, SLR-S2, and SLR-S3) at the Miura site. SLR-CP0 denotes the telescope reference point of the KSP-SLR. VLBI-CP0 denotes the origin of the antenna of the KSP-VLBI.

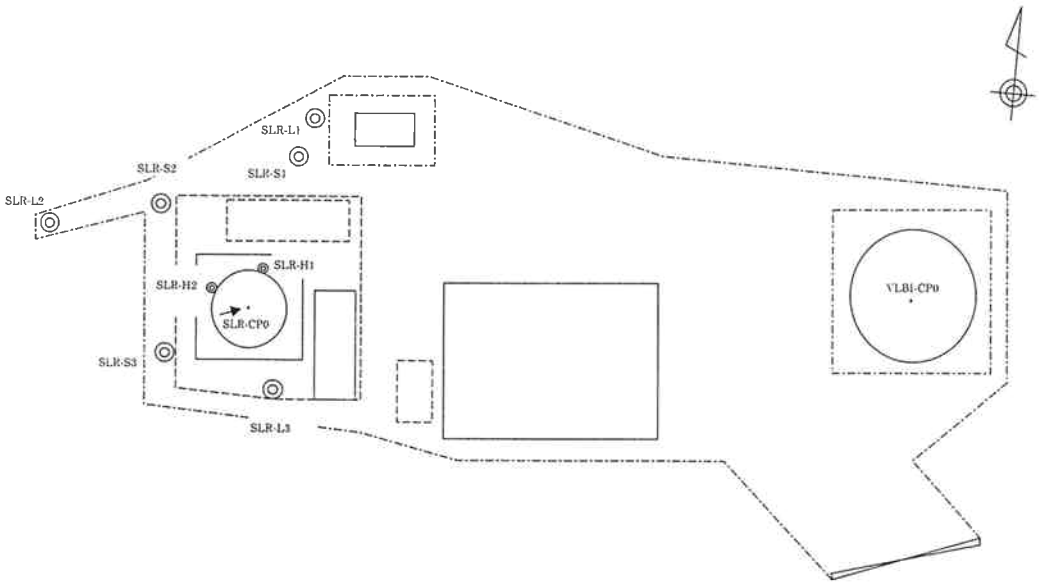


Fig. 7 The configuration of the pillars (SLR-L1, SLR-L2, and SLR-L3), benchmarks (SLR-H1 and SLR-H2), and short pillars for ground survey (SLR-S1, SLR-S2, and SLR-S3) at the Tateyama site. SLR-CP0 denotes the telescope reference point of the KSP-SLR. VLBI-CP0 denotes the origin of the antenna of the KSP-VLBI.

Fig. 4 shows the configuration of the ground targets and short pillars for ground survey at the Koganei site. In the Koganei site, the pillars were installed about 10 to 25 m away from the telescope reference point. The benchmarks were installed about 10 m under the telescope reference point. SLR-CP0 denotes the telescope reference point of the KSP-SLR. VLBI-CP0 denotes the origin of the antenna of the KSP-VLBI. The position of the short pillar S2 was adopted as the station reference point at each site of the KSP-SLR.

Fig. 5, 6, and 7 show configurations of the ground targets and short pillars for ground survey at the

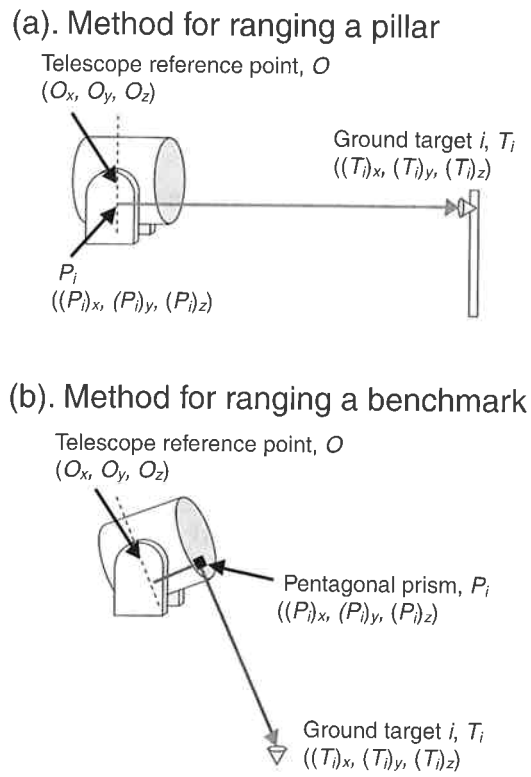


Fig. 8 Method of ranging the ground target.

Kashima, Miura, and Tateyama sites respectively.

3. Estimating the Telescope Reference Point and System Delay

After the ground targets are ranged, the position of the telescope reference point and the system delay can be estimated at the same time with our method. This section explains the method.

Fig. 8 shows how to range the ground targets about the pillar and the benchmark. The pointing angle of the telescope must be shifted so that the second mirror of the telescope[2] does not interrupt the laser beam while ranging to the pillar as shown in Fig. 8 (a). A position on the wave front of beam passing through the telescope reference point at ranging time for the # ith target is called point P_i. As shown in Fig. 8 (b), the ranging to a benchmark was done using the pentagonal prism, which changes the direction of the laser beam 90 degrees to compensate for the limited elevation angle of the telescope. The position of the middle of the prism at ranging time for the # ith target is called point P_i.

In this way, by determining P_i, observation equation can be common for both of the pillar and the benchmark as

$$\rho_i = \frac{\sqrt{\{(T_i)_x-(P_i)_x\}^2+\{(T_i)_y-(P_i)_y\}^2+\{(T_i)_z-(P_i)_z\}^2}}{c/n}+\delta+\delta P_i$$

$$= \frac{\sqrt{\{(T_i)_x-O_x-(\overrightarrow{OP_i})_x\}^2+\{(T_i)_y-O_y-(\overrightarrow{OP_i})_y\}^2+\{(T_i)_z-O_z-(\overrightarrow{OP_i})_z\}^2}}{c/n}$$

$$+\delta+\delta P_i\ ,$$

where ρ_i is the raw range value of one way to each # ith ground target, $(T_i)_x$, $(T_i)_y$, and $(T_i)_z$ are the three-coordinates of the # ith ground target, O_x, O_y, and O_z are the three-coordinates of the telescope reference point, $\overrightarrow{OP_i}$ represents the relative vector which goes to P_i from the telescope reference point, δ is the system delay, δP_i is the reaching time to point P_i of the wave front of beam passing through the telescope reference point, c is the constant of the speed of light, and n is the refractive index in the medium.

We can calculate $(T_i)_x$, $(T_i)_y$, $(T_i)_z$, $\overrightarrow{OP_i}$ and δP_i by using values from the survey. δP_i is zero in the case of the pillar, and δP_i is the reaching time to point P_i of the wave front of beam passing through the telescope reference point in the case of the benchmark.

Therefore, O_x, O_y, O_z and δ can be estimated by the least squares method by forming coalition with more than four observation equations for each independent ground target.

4. Conclusions

The position of the telescope reference point could not be referred to directly in the usual laser ranging system in measuring the system delay. Our new calibration method enables us to estimate not only the system delay but also the telescope reference point by ranging each of five groundtargets. Our method makes it possible to monitor the changes in the position of the telescope reference point over a long period, and to precisely calibrate the sate-llite laser ranging data by using the estimated system delay.

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